

Condition-based Maintenance for Highly Engineered Systems

A CHAOS BASED MONITORING AND DIAGNOSTICS TOOLBOX FOR INDUSTRIAL APPLICATION

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ABSTRACT

The paper describes the guidelines of a research presently under development. In various operating conditions rotating machines and in general nonlinear mechanical systems may vibrate chaotically; this is e.g. the case of rubbing between rotor and stator, of oil-whirl in bearings, of rotor cracks, and of other typically nonlinear phenomena. By processing sensors signals taken from the system, monitoring modules, mainly based on chaos quantifiers, make possible to detect the presence of nonlinearities and therefore to pinpoint, at an earlier time than the traditional methods, the presence of anomalous chaotic operating conditions. A measure of the quantity of chaos may be used as a diagnostic indicator. The authors are developing a toolbox of software modules for monitoring and diagnostics based on chaos theory. Special filtering techniques are provided for processing signals of experimental origin. To test the software, time histories of various instabilities are generated using an experimental instrumented model of rotor. The integration of the innovating modules for monitoring and diagnostics with the traditional software and the creation of a database for diagnosing damage and/or trend to damage will be the basis for condition monitoring.

1. - INTRODUCTION

Chaos tracking techniques will likely be adopted in future monitoring and diagnostic systems for assessing machinery conditions. E.g. [2] examines rotor rub impact and reports the results obtained with conventional techniques (FFT, orbit) and with Poincaré maps and other chaos theory methods. Poincaré mapping clearly detects a 3% difference in bearing damping, an event not detected by FFT. The same fact holds for the value of fractal dimension. One can see a change in the pattern of the Poincaré map and the fractal dimension that neither the FFT map nor the vibration orbit clearly show. So it becomes clear that what has been traditionally considered background noise and thus filtered out in fact contains valuable diagnostic information.

Chaotic vibration is an oscillatory motion which is not periodic, not quasi-periodic (i.e. with two or more incommensurate frequencies) and not random. A chaotic system is a deterministic system whose time history has a sensitive dependence on initial condition. Nonlinearity is the necessary, but not sufficient, condition for chaos vibration. Important examples of chaotic behavior can be found in rubbing between rotor and stator casing (a major contributor to failure and excessive maintenance in steam or gas turbines, pumps, compressors, generators, motors, etc.), in cracked rotors, in bearings, in gearboxes, etc. Nonlinearity can arise from nonlinear elasticity, nonlinear damping, backlash, fluid related forces, magnetic or electric forces, etc [see e.g. 13, 18, 19, 20, etc.]. An attractor is a set of points or a subspace in the phase plane toward which a time history approaches after transient die out. Classical attractors are associated with classical geometric objects in the phase plane (equilibrium with a point, periodic motion with a closed curve, quasi periodic motion with a toroidal surface), chaotic motion corresponds to a “strange attractor”, associated with an object, called fractal, which is new with respect to the objects known from classical geometry. A qualitative descriptor of the evolution of chaos is the Poincaré map, which is a sequence of dots in the phase plane, obtained by stroboscopically plotting in the phase plane the dynamic variables at some particular

phase of the forcing function. For a chaotic system it has a fractal structure, i.e. it is an infinite set of highly organized points such that, zooming a portion of the Poincaré map and observing further the structure, the structured set of points continues to exist (self similarity of the chaotic attractor). Another characteristic of chaotic systems is the generation of a continuous spectrum of the Fourier Transform (FFT) for a single frequency excitation. Quantitative indicators of chaos are available (e.g. the Lyapunov exponents and the measures of dimension).

The goal of the research reported hereafter is the development of a toolbox for monitoring and diagnosing the chaotic behavior of rotating machinery, to be run in parallel and integrated to the traditional techniques. In the future it will be extended to any mechanical system. A large effort will be devoted to develop techniques to associate the diagnosis parameters (chaos quantifiers) to the amount of damage and to the trend to damage, and to the evaluation of the time available for a maintenance action and of its economic convenience.

2. - SOFTWARE MODULES FOR MONITORING, DIAGNOSTICS AND FILTERING

The structure of the toolbox is evolving day by day. We will show its present aspect, to illustrate its various features. The software is written in MATLAB. Fig.1 is an initial window, showing that also a demo is provided to illustrate the various possibilities and to help to learn the procedures.

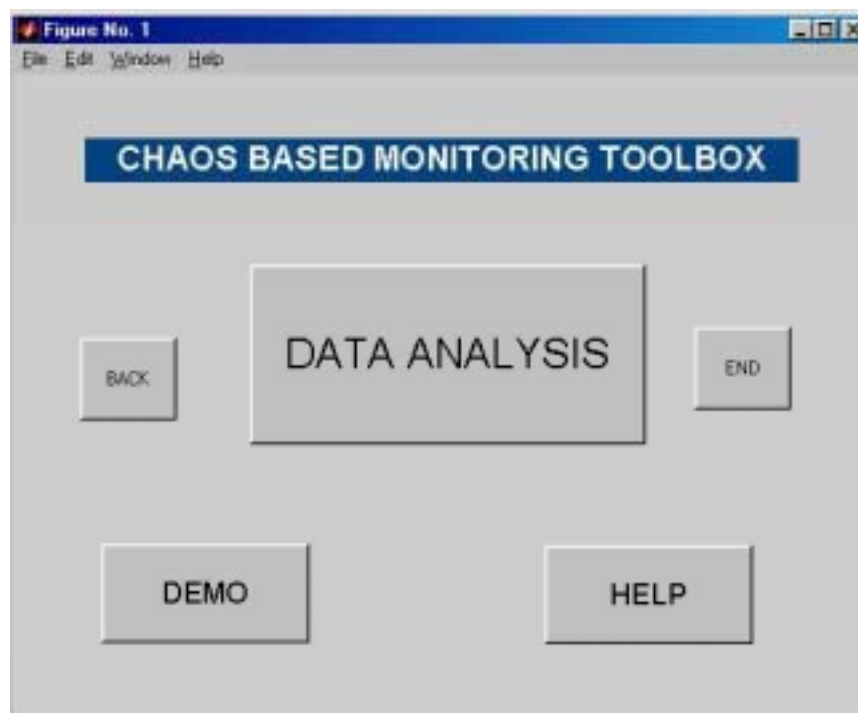


Fig.1 - Initial window

Fig.2 shows the other option, i.e. data analysis. We can perform data acquisition, we can process experimental data, we can recall a previous workspace or examine computer-simulated data. Fig.3 shows various choices: filtering, symbolic analysis, traditional methods, and chaos quantifiers.

Experimental signals are always affected by noise. Noise can modify the chaos quantifiers; a wrong filtering can cause the same problem. Special filtering software for chaotic signals is under development. In particular we wrote (and tested on experimental signals coming from an instrumented model of rotor) a specific filtering software for signal noise reduction based on iterative SVD decomposition, according to the method suggested by Shin, Hammond and White [4]; singular value decomposition is used iteratively to distinguish the deterministic signal from the noise. The algorithm makes possible to eliminate noise in a time series keeping unmodified its chaotic component; under certain conditions the method may be used

almost blindly, even in the case of a very noisy signal. It is not only applicable to chaotic signals but also to ordinary deterministic waveforms.

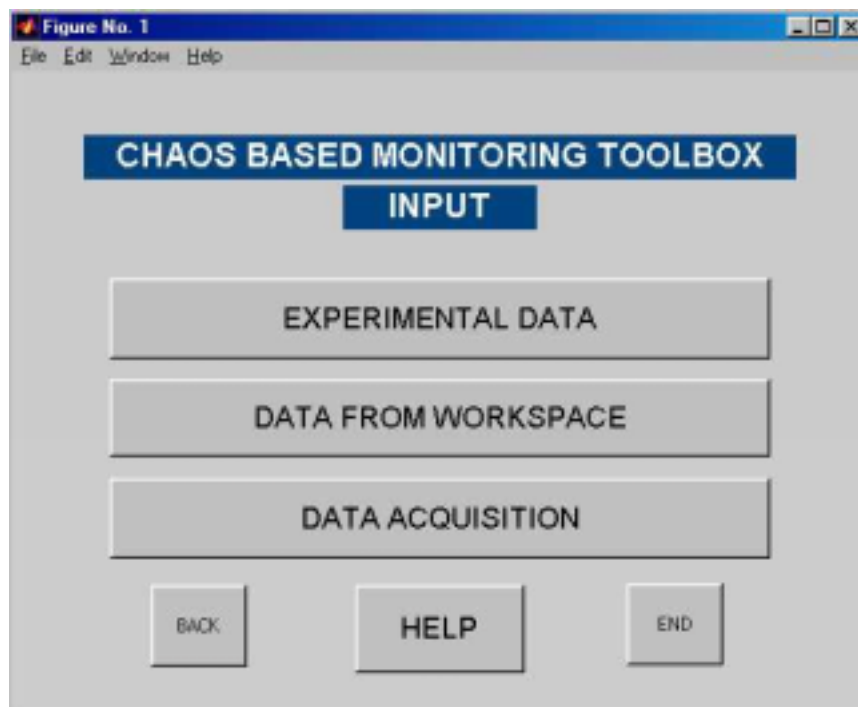


Fig.2 - Input window

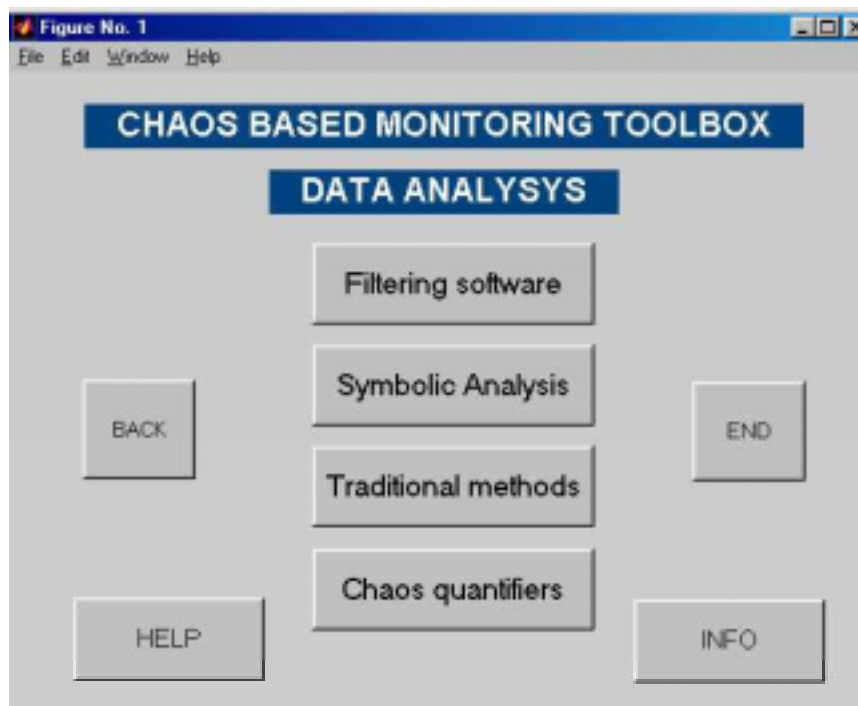


Fig.3 - Data analysis window

Symbolic time series analysis is another option, which can be very useful in some cases. Data symbolization provides a simple, yet effective way to minimize the effects of noise, when it hides the underlying deterministic part; it helps to separate unstructured small-amplitude noise from significant large-

amplitude trends. Symbolization [23] is based on partitioning, i.e. on the conversion of a data series of many possible values into a symbol series of only a few distinct values. The number n of these distinct values is the symbol-set size, called alphabet size. The simplest possible partition is the binary partition ($n=2$). In this case we choose a threshold (typically the median value of data to get an equiprobable partitioning) and we assign the value 1 to data larger than the threshold and the value 0 to the data values smaller than the chosen cutoff value. Instead of this static transformation one could perform a dynamic transformation, i.e. not based on a certain level but on the difference between two adjacent measurements. The next step is to select a standard number of sequential measurements, obtaining a symbol sequence, called word. Each symbol sequence obtained from the measurements is converted into a sequence code by converting the base- n sequence into a corresponding base-10 number. E.g. for a binary partition and a word having length 3, for the sequence 000 the sequence code is 0, for the sequence 011 the sequence code is 3, etc. Then we observe the frequency of occurrence of each sequence code (number of times each sequence occurs divided by the number of observed frequencies), creating a symbol-sequence histogram, i.e. making a symbol statistics. Equiprobable partitioning will give a flat histogram for a random time series, while non-random patterns will give origin to peaks in the histogram. For characterizing symbol-sequence histograms various methods are available, such as modified Shannon entropy, Euclidean norm, modified χ^2 , and, more in general, all the measures of complexity in symbolic dynamics. We can distinguish between traditional complexity measurements (Shannon entropy, algorithmic complexity, approximative entropy), which are measures of randomness, since they are maximum for white noise, and alternative complexity measurements (renormalized entropy, ε -complexity) which are not maximum for purely random behavior. Another useful indicator is mutual information, i.e. a generalization of the correlation function expressing the average dependence of two symbols over N time steps; for chaotic time series mutual information decreases with growing N , while periodic waveforms exhibit peaks at multiple of the period.

Chaos quantifiers are another option available in the toolbox. Fig. 4 shows a number of indicators presently under development and test in the software. Various aspects are of interest, e.g. their sensitivity, the computer time necessary for their computation, the effects of the length of the time series, the influence of noise, etc. We are testing the largest possible number of chaos indicators to decide which of them will be included in the final version of the toolbox.

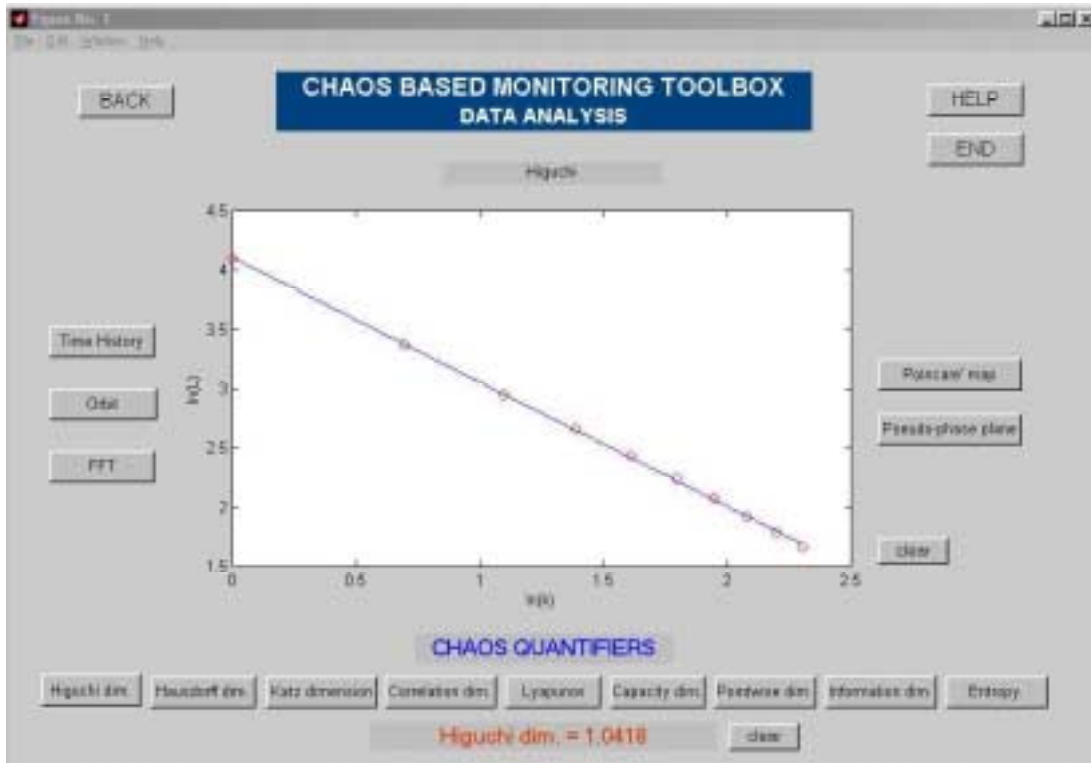


Fig.4 – Chaos quantifiers window for the case of Higuchi dimension calculation

The Lyapunov exponents test evaluates the sensitivity of the system to changes in initial conditions; a positive exponent means that nearby orbits diverge. Positive Lyapunov exponents imply chaotic dynamics. As far as a criterion for chaos is concerned, one has only to examine the largest Lyapunov exponent and check if it is positive. From the Lyapunov exponents (the set of Lyapunov exponents is known as the Lyapunov spectrum), the Lyapunov dimension can be obtained.

The measures of dimension evaluate the extent to which orbits will fill a certain subspace and a noninteger dimension is a hallmark of a strange attractor. In simple words the dimension of an attractor is a measure of its “fractalness”. Many definitions of dimension exist [see e.g. 1, 7, 8, 9, 10, etc.]; we are developing various modules according to the various definitions. We have done a preliminary comparison between Higuchi dimension, Hausdorff dimension and Katz dimension. The tests have used both reference signals whose properties are known from bibliography and experimental waveforms, also checking the effects of varying time series length or of the presence of noise. The Higuchi method better approached the reference values with all kinds and lengths of the waveforms, and was relatively fast; its implementation is reasonably simple.

Other options in the toolbox are the Poincaré maps, the maps in the pseudo-phase plane (Fig.5), and the plots of orbits, of time histories, of FFTs.

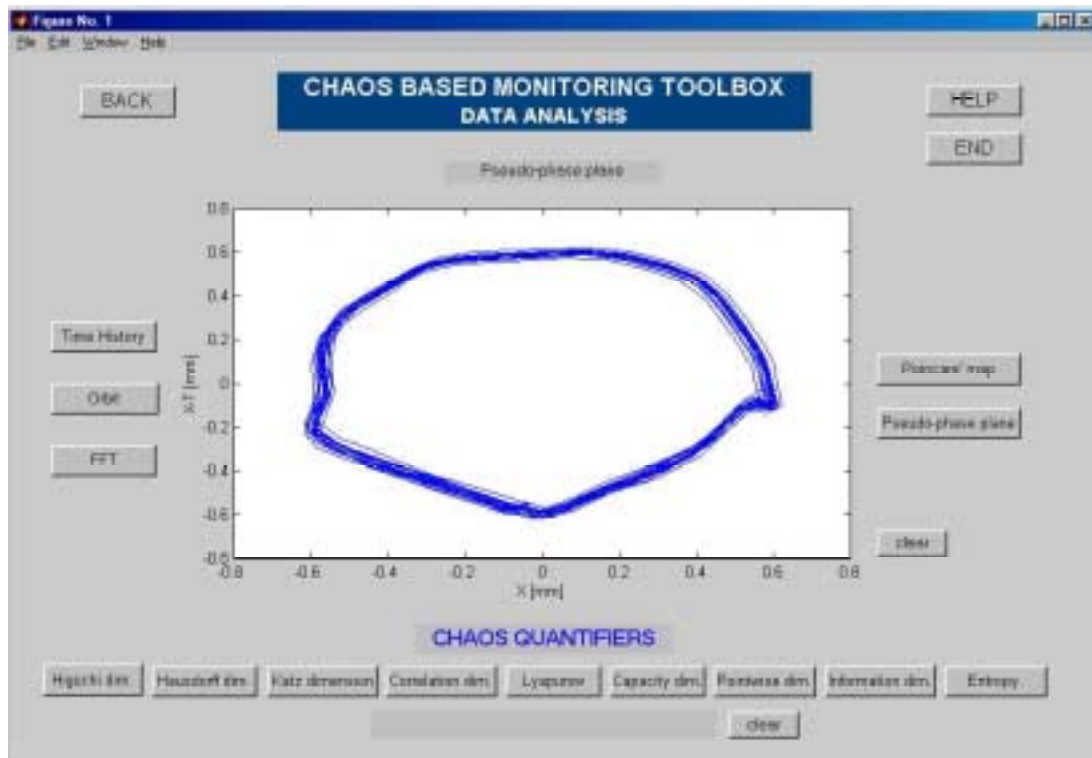


Fig.5 – Pseudo-phase plane plot

To perform the tests of the modules, computer-generated data may be useful for the preliminary tuning, but experimental data are required for a true evaluation and validation. The problem is to have available enough significant data files corresponding to instabilities and critical conditions of industrial plants or machinery. While obviously we rely as much as possible on industrial cooperation to examine true industrial data files, we make also a large use of an experimental instrumented model, the Bently Nevada Rotor Kit, which is able to create at will various critical conditions, changing rotor speed, shaft bow, rotor stiffness, unbalance, shaft rub, bearing operation conditions, etc. Fig.6 shows presence of chaos due to rubbing; other tests have been done for oil whirl conditions. In both the cases of rubbing and oil whirl, the Higuchi dimension varied of a sensible amount in presence of a chaotic behavior.

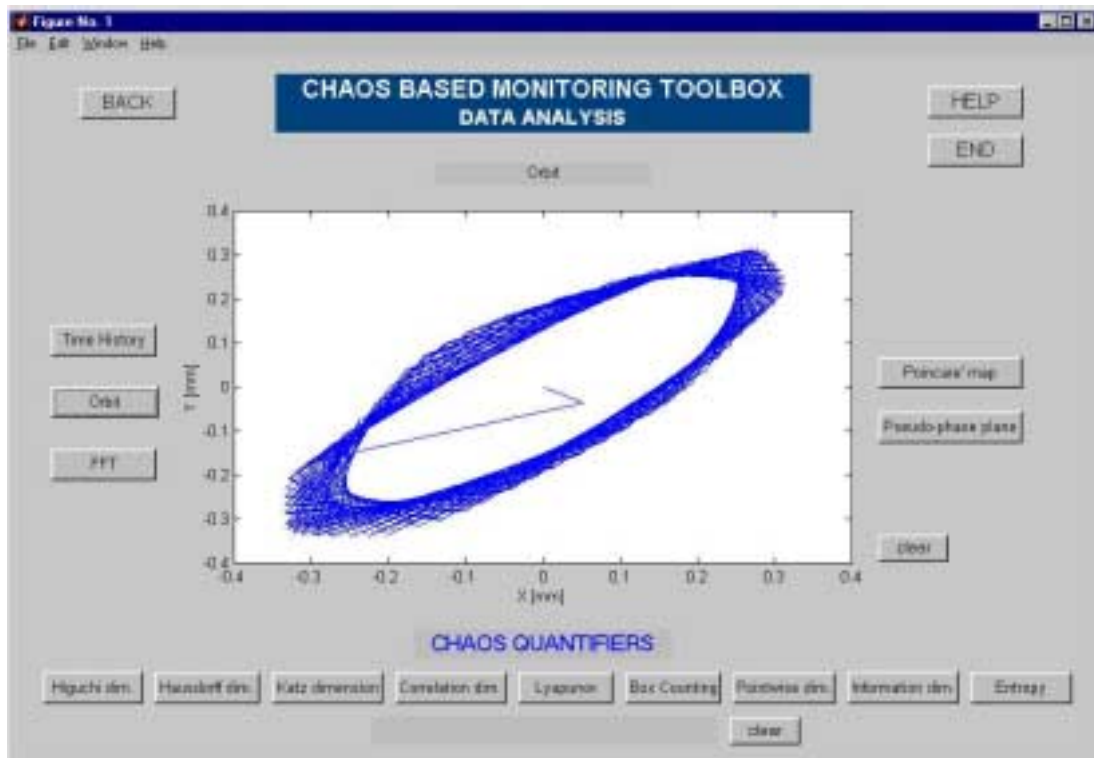


Fig.6 - Vibration orbits measured in a rubbing test ($n=6000$ rpm)

3. CONCLUSION

Chaos-based monitoring can add useful diagnostic information for rotating machinery or mechanical systems, supplementing the traditional methods.

The preliminary work performed provides a strong motivation for further developments. Since the final goal is a condition monitoring system, which must also collect the information from different modules, it will be necessary to establish, for the application under examination, the correlations between diagnostic parameters (from the modules) and damage parameters and to formulate, as a synthesis of these correlations, a single function summarizing the state of health of the machine, i.e. the amount of damage and the rate of trend to damage.

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